Complete Velocity Distribution in River Cross-sections Measured by Acoustic Instruments

Ralph T. Cheng and Jeffrey W. Gartner
U. S. Geological Survey
Menlo Park, California
(650) 329-4500
rtcheng@usgs.gov

Abstract -- To fully understand the hydraulic properties of natural rivers, velocity distribution in the river cross-section should be studied in detail. The measurement task is not straightforward because there is not an instrument that can measure the velocity distribution covering the entire cross-section. Particularly, the velocities in regions near the free surface and in the bottom boundary layer are difficult to measure, and yet the velocity properties in these regions play the most significant role in characterizing the hydraulic properties. To further characterize river hydraulics, two acoustic instruments, namely, an acoustic Doppler current profiler (ADCP), and a "BoogieDopp" (BD) were used on fixed platforms to measure the detailed velocity profiles across the river. Typically, 20 to 25 stations were used to represent a river cross-section. At each station, water velocity profiles were measured independently and/or concurrently by an ADCP and a BD. The measured velocity properties were compared and used in computation of river discharge. In a tow-tank evaluation of a BD, it has been confirmed that BD is capable of measuring water velocity at about 11 cm below the free-surface. Therefore, the surface velocity distribution across the river was extracted from the BD velocity measurements and used to compute the river discharge. These detailed velocity profiles and the composite velocity distribution were used to assess the validity of the classic theories of velocity distributions, conventional river discharge measurement methods, and for estimates of channel bottom roughness.

I. Introduction

Flows in open channels and natural rivers are often described by the simplifying cross-section averaged one-dimensional hydraulic equations. In reality, river hydrodynamics is quite complicated because the river cross-sections and riverbed are usually complex, and do not meet assumptions of one-dimensional flow. While the one-dimensional approximation is quite useful in practical applications, it is important to assess the extent and the impacts of the approximations. For example, in the river discharge measurement procedure recommended by the U. S. Geological Survey (USGS), the mean velocity is determined by the average of velocities measured at the vertical locations 20% and 80% of the water depth [1]. If the water is shallow, the mean velocity is assumed to be the same as the velocity measured at 60% of the water depth. These guidelines are based on the assumptions that the river flow is basically one-dimensional and steady and the width to depth ratio is quite large (much greater than 5), so that velocity profiles in the river cross-section are not affected by the presence of banks. The velocity distribution is assumed to be a fully developed turbulent boundary layer whose velocity profile can be approximated by the log-law-of-the-wall [2]. On the basis of these assumptions, tens of thousands of river discharge measurements have been made using mechanical current meters to determine the velocities at 20% and 80% of the water depth for the computation of river discharge. The discharge measurements were used to establish a stage-discharge relation from which the river discharge is deduced indirectly from monitoring the stage values [1]. Although voluminous historical 0.2 and 0.8 velocity measurements exist, they do not provide sufficient information for assessing these simplifying assumptions or for validation of the boundary layer theories [2]. Some limited laboratory data are available, which may be used to guide theoretical developments [3], [4]; however, the flow properties in natural rivers might deviate substantially from laboratory conditions.

With the advances of acoustic Doppler current profiler (ADCP) technologies, a moving boat discharge measurement technique is gradually replacing the classic procedure using mechanical meters when the water is sufficiently deep for ADCP applications [5]. In an ADCP discharge measurement, the transducers of an ADCP are mounted facing down and barely submerged under the water surface. They ping continuously while the boat is traversing from bank to bank. The boat motion is monitored by bottom tracking acoustic pings or by a global positioning system (GPS). The water flux crossing the vertical plane of the boat path is computed, which is the same as the river discharge. However, there are three zones in which the velocities cannot be measured by the ADCP; in these zones the flow properties must be estimated. First, the velocity is not measured in a surface layer whose thickness is the sum of the distance from the free-surface to the ADCP transducer head plus a blanking distance between the transducer head and the first measurement bin. Second, the velocity cannot be accurately measured in a layer near the bed due to side-lobe interference (at least 6% of water depth for a 20^o beam ADCP). Third, the water depth is usually too shallow near the river banks for the ADCP to perform. In these three regions, analytical solutions are used to estimate the flow properties for discharge computations, and the extent of errors introduced in this discharge procedure is not known precisely. Furthermore, the standard error of a single ping ADCP measurement is quite large and variable depending upon the specific data processing mode used by the ADCP. While the continuous ADCP measurement on a moving boat is a very powerful method for determining the river discharge, the individual velocity profiles extracted from these records are too noisy to be useful to aid assessment or validation of basic theories in river hydraulics.

The ADCP can be used for measuring a velocity profile in the vertical when the ADCP is held at a fixed position for taking a large number of the single ping velocity measurements. The averaged single ping velocity profiles reduce the measurement errors so that a meaningful mean velocity profile can be obtained. In spring 2002, a field experiment was carried out by the USGS in the San Joaquin River at Vernalis, California to evaluate a microwave radar system for determining water surface velocity and a non-contact methodology for river discharge measurement [6, 7]. A cableway was established across the test section of the river on which a variety of instruments could be attached. Some instruments were towed across the river, and others held in position for velocity measurements over an extended period of time.

To achieve the objective of measuring velocity distribution in the complete river cross-section, a BB-ADCP, and a BoogieDopp (BD) were used. The river cross-section was divided into 21 stations. At each station the ADCP and the BD were held in position for continuous pinging to yield mean velocity profiles for that location. The ADCP was also towed across the river to arrive at a "moving boat" ADCP discharge measurement for comparison with other independent discharge measurements. In the following sections, the salient characteristics of ADCP and BD are discussed. The velocity profiles measured by the ADCP and by the BD are compared and discussed. After examining properties of the velocity profiles, a composite velocity distribution in the river cross-section is constructed. Hydraulic properties of the river are further deduced from these measurements and their implications are discussed.

II. Instruments and Deployments

II.A Acoustic Doppler Current Profiler

An ADCP can be deployed with the acoustic beams pointing vertically up or pointing vertically down. In this study, the ADCP was mounted in the middle of a small trimaran with the transducers oriented down and just submerged below surface. The trimaran was tethered to a cableway; by controlling the movements of the cable, the trimaran could be towed across the river to replicate a "moving boat" ADCP discharge measurement or could be kept stationary for velocity profile measurements. There are several modes of ADCP operation that could be selected for these measurements depending upon the water depth and other considerations. A detailed discussion of the subject is given by Gartner and Ganju [8]. Typically, the highest sampling rate and finest usable bin-size were chosen to give maximum spatial resolution of velocity distribution. A 1200 KHz ADCP was used with the bin-size set to 25 cm. Adding appropriate blanking distance, the first bin of velocity was measured at about 75 cm below surface. Each single-ping velocity measurement was saved; these high frequency velocity data could be used for further analysis of the turbulence properties of the flow in the water column. By considering the local water depth and flow conditions, generally the RDI-mode-1 was used in the ADCP fixed station measurements, which included more than 400 single-ping samples. The entire procedure took about 3 minutes per station to complete.

II.B BoogieDopp (BD)

The BD is a fairly new acoustic instrument designed for river discharge measurements in small and shallow rivers. BD has three acoustic beams operating at 2 MHz. Two vertical beams point downward at 25^o angle forward and aft from the vertical, and a third beam points forward at 20^o from the horizontal (Fig. 1).

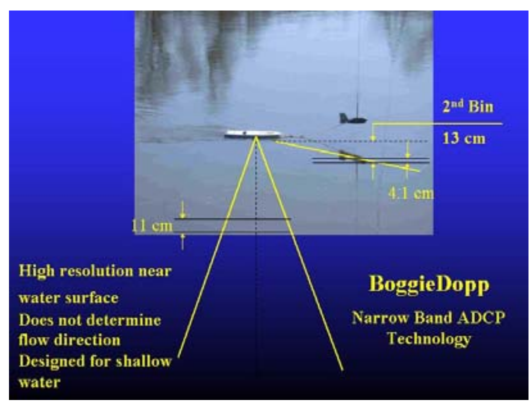

Fig. 1. The physical orientation of the acoustic beams of a BoogieDopp (BD)

These acoustic beams operate in a mode similar to a narrow band ADCP. The orientation of the forward beam is designed to measure velocity in a surface layer of the water column in high vertical resolution. The acoustic beam assembly is mounted on floating platform (a boogie board), which is tethered and oriented in the direction of the moving stream. The BD assumes the direction of the flow (for the entire water column) is the same as the longitudinal axis of the BD during the measurement. All three beams are operating with the same setup. If the vertical bin-size is set to 11 cm, then effectively the bin-size of the forward beam is 4.1 cm. Since BD is a new instrument, it was evaluated in a tow tank at the U. S. Geological Survey's Hydraulics Test Facility at Stennis Space Center, Mississippi. The tow tank is 3.7 m (12 ft) wide, 3.4 m (11 ft) deep, and a usable 106.7 m (350 ft) long. The BD was towed for a minimum of 50 seconds with towing speeds ranging from 0.5 ft/sec to 5 ft/sec. Based on the tow tank evaluation, a constant correction factor of 10.6% and 17% is applied to the velocities produced by the downward and forward looking beams using the beta-version of the BD firmware. (Recent firmware improvements have eliminated use of large correction factors in production versions of the BD.) After applying the correction factors, the errors in the measured velocities are maintained to within 3% for the downward beams, and 4% for the forward beam when compared to towing speeds in the velocity range between 1 and 5 ft/sec. The vertical bin-size was set to 11 cm, and the variance of the velocity in the downward pointing mode seems to be minimal. The measured velocity in the first bin of the forward beam is typically biased ~15% low for a variety of possible reasons; the remaining velocities show consistent accuracy. Thus the measured velocity in the first bin is discarded and not used in field applications. The velocity in the second bin, which is located at about 11 cm below the water surface is considered the first valid measurement.

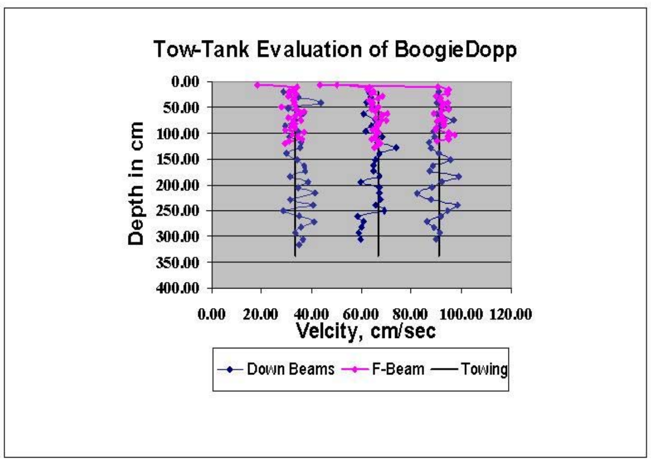

Fig. 2. Samples of tow-tank evaluation of BoogieDopp, the towing speeds at 33.4, 66.7, and 91.0 cm/sec are shown in solid lines. The velocities measured by the downward looking and forward looking beams are compared with the respective towing speed.

Samples of the towing tank results are shown in Fig. 2 with the towing speeds clocked at 33.4, 66.7, and 91.0 cm/sec (solid line). The velocities measured by the downward beams are shown in blue and the near surface velocities measured by the forward-looking beam are shown in pink. The velocity in the first bin of the forward-looking beam should be discarded, but they are shown in the figure for illustration.

III. Results

Between March 15 and May 17, 2002, the USGS conducted an extensive flow measurement experiment on the San Joaquin River at Vernalis, California for the purpose of evaluating radar technologies for continuous non-contact river discharge measurement [9]. Numerous ADCP and BD velocity and discharge measurements were made as part of that experiment. Whenever possible, both the ADCP and the BD were kept at the same station to obtain concurrent mean velocity profiles (Fig. 3), these independently measured velocity profiles are compared.

Fig. 3. An ADCP mounted on a trimaran and a BD are tethered together to collect concurrent vertical velocity profiles. Each instrument transmits data through its own radio-modem operating in distinct frequencies.

III.A Velocity Profiles

At the experiment site, the width of the San Joaquin River is about 68.8 m (225 feet). The maximum depth is about 7 m, with an averaged depth of 3.5 m. The river cross-section was divided into 21 stations; at each station the vertical velocity profiles were measured concurrently by an ADCP mounted on a trimaran and a BD. For BD, the downward looking bin-size is set to 11 cm; considering the blanking distance, the first velocity measurement is estimated to be at about 21 cm below free-surface. Although the bin-size of the forward beam is also 11 cm, the equivalent vertical resolution is 4.1 cm. By discarding the velocity in the first bin, the first valid velocity measurement (second bin) is estimated at about 11 cm below the water surface.

The vertical velocity distributions measured by the ADCP, the downward and forward pointing acoustic beams of the BD at the station 19.8 m (65 ft) from the left bank are shown in Fig. 4. All measured velocities are in good general agreement when data are available for comparison. The forward beam of the BD measures the velocity closest to the water surface and provides the finest vertical resolution. The velocity distributions in the over-lapping region measured by the forward looking beam and downward looking beams of the BD are in very close agreement, but the vertical spatial resolution in the downward mode (11 cm) is nearly three times the size the forward beam (4.1 cm).

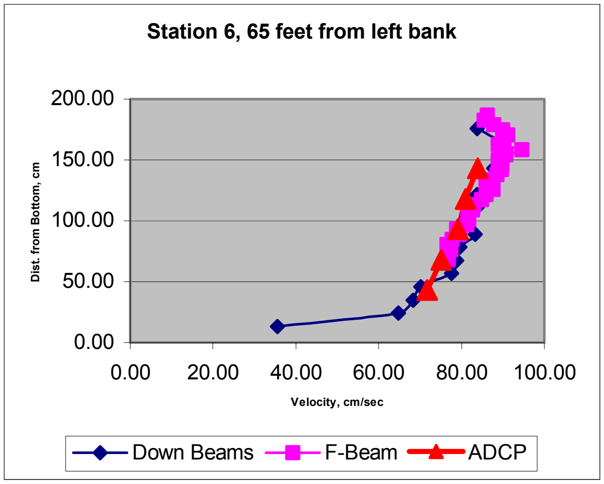

Fig. 4. Comparison of the vertical velocity distributions at Station 6 measured by the BD using downward and forward looking beams, and the velocity distribution measured by an ADCP with a bin-size of 25 cm. The first velocity measured by the ADCP is 75 cm below surface.

Clearly, the ADCP is limited in its ability to measure velocity near the free surface. Furthermore, the vertical spatial resolution is relatively coarse (25 cm). The velocity profile determined by the ADCP shows smaller velocity gradient (shear) than the BD measurements; this could be the result of coarse spatial resolution and spatial averaging of velocities. The measured velocity distribution by the BD in the surface layer suggests that a maximum velocity exists below the free surface. Since wind was weak during the time of the measurements, the probable cause of the maximum velocity below the free-surface is the presence of secondary circulation. This station is close to the left bank and near the location where the water is deepest in the cross-section. The geometry of the channel cross-section is conducive for the development of secondary flow. The presence of secondary circulation is more evident in the composite display of velocity distribution in the river cross-section to be discussed in the next section.

Similar comparisons of the velocity profiles measured at 38.1 m (125 ft) from the left bank are shown in Fig. 5. The effect of secondary flow is evident at this station (also see Fig. 8 for the velocity distribution in the river cross-section). Since the ADCP cannot measure velocity within 75 cm of the free surface, the subtle and important velocity distributions near the surface cannot be detected. This is most critical in shallow water where unmeasured regions near the surface and near the bottom make up a larger percentage of the total water column. Thus, it is important to use only the appropriate measuring device if the velocity properties in the region near the free surface are to be resolved.

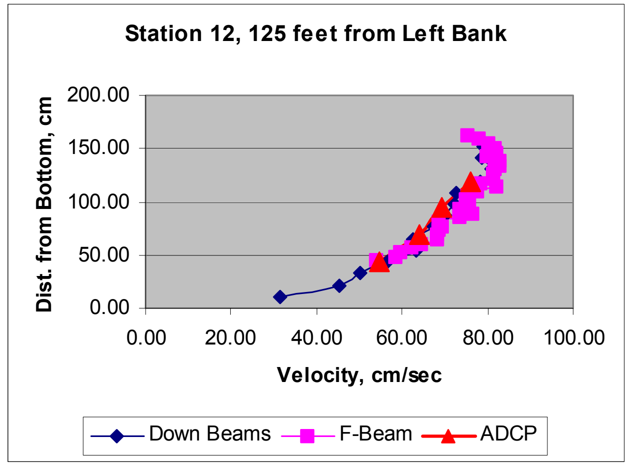

Fig. 5. Comparison of the vertical velocity distributions at Station 12 measured by the BD with bin size of 11 cm and 4.1 cm for the downward and forward beams respectively; and the velocities measured by an ADCP with a bin-size of 25 cm.

III.B Composite Velocity Distribution at a River Cross-section

Twenty-one vertical velocity profiles measured by the BD are combined to give a composite plot showing the complete velocity distribution in a river cross-section in Fig. 6. The river channel is asymmetric with deeper channel near the left bank. Near the water surface and water sediment boundaries, the velocity is not measured. These 'blanked out' regions are much reduced by use of the BD. The overall velocity properties are clearly depicted in the cross-sectional plot. The consistent presence of a maximum velocity core, which is located near the left bank of the river, was possibly due to the presence of secondary flows and the channel geometry.

III.C Other Hydraulic Properties

The composite velocity distribution data can be further analyzed to reveal properties of river hydraulics. Measuring river discharge is always an important task in water resources management. The present measurement practices are labor intensive and often expose field technicians to potential hazards. There is a strong consensus suggesting that it is desirable to develop a method for remotely sensing river discharge [6], or at least to research and develop other procedures that simplify the present river discharge measurement procedures [7, 9]. Following this development, it is believed that water surface velocity can be used as an index velocity with which the water column mean-velocity can be estimated for computing the river discharge.

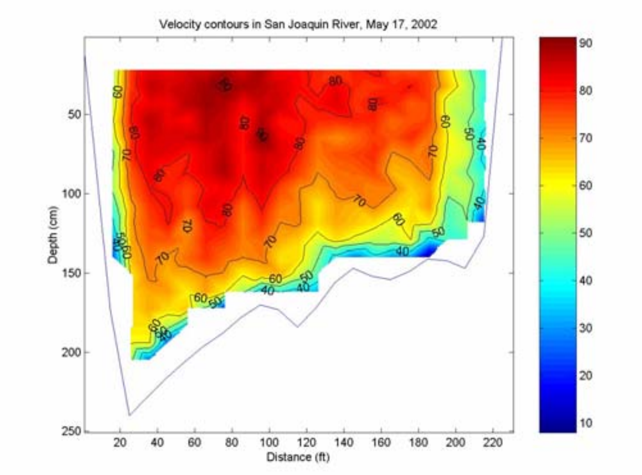

Fig. 6. Complete velocity distribution in a cross-section of San Joaquin River at Vernalis, California. The velocities were measured by a BD on May 17, 2002.

Based on the velocity profiles measured by the BD, the water column mean velocity is computed. The mean velocity is plotted against the surface velocities measured in the first bin of the downward beams and the second bin of the forward looking beam in Fig. 7. It is interesting to note that the independently measured surface velocities are in very close agreement except at two stations. The cause of the discrepancy at these stations is not known. If the velocity profile follows the log-law-of-the-wall [2], the theoretical ratio of mean velocity over surface velocity is 0.85. The measured ratio varies between 0.80 and 0.93. The higher values are found near the core of high velocity where maximum velocity is located below the water surface. In this region, the velocity in the near surface layer does not follow the log-law-of-the-wall. In contrast, low ratio values are found in shallow regions where the measuring instrument could not provide sufficiently fine resolution and/or accurate velocity measurements. In this experiment on May 17, 2002, the mean value for the mean to surface velocity ratio is 0.88, which is reasonably close to the theoretical value of 0.85.

The ADCP was towed on a temporary cableway at the river cross-section to replicate "moving boat" discharge measurements giving an averaged value of 70.2 cubic meters per second (cms) (or 2476 cfs). The BD discharge measurement based on the firmware was 76.85 cms (2712 cfs). The discharge computed from the measured surface velocities as index is 75.32 (2658 cfs). During the ADCP discharge measurements, there were some movements of the river bed detected by the bottom tracking measurements. The effects of a moving bottom are not removed from the ADCP discharge measurements, thus the reported river discharge is biased low. With this consideration, the ADCP and BD discharge measurements are in reasonable agreement. Thus these results imply that the surface water velocity could be used as the index for computing the river discharge.

Finally, the measured velocity profiles can be used to estimate the bottom shear stress, roughness length and turbulent mixing in the cross-section of a river [10, 11]; however, these subjects are beyond the scope of this paper and will not be discussed further.

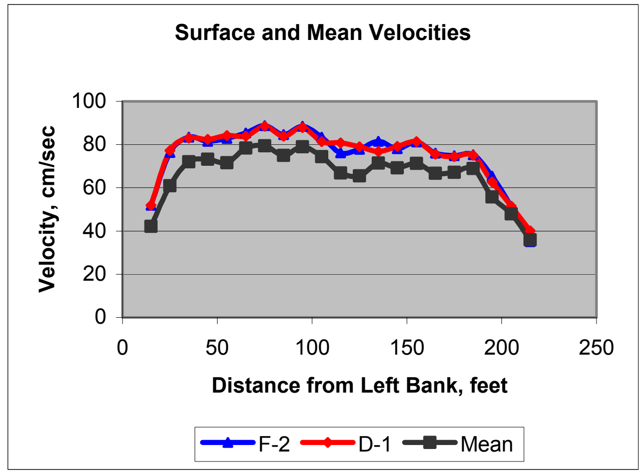

Fig. 7. Distribution of surface velocity determined by downward and forward beams of a BD, and the distribution of the water column mean velocity.

IV. Discussion and Conclusion

River hydraulics is quite complex in natural channels and rivers. For practical and engineering purposes, the flows in river channel are often characterized by depth averaged or cross-sectionally averaged properties. While these simplifications might be justifiable and necessary for practical reasons, it is important to be cognizant about the complex nature of the three-dimensional free-surface flows in rivers and open channels. A better understanding of the hydraulic properties in natural rivers would give rise to a more accurate approximation in practical applications. In this study, the velocity distribution in a river cross-section has been investigated in detail. The complete velocity distribution in the river cross-section was measured by a BD, an instrument that is capable of measuring water velocity starting at 11 cm below the water surface. The downward and forward acoustic beam systems give vertical velocity resolution at 11 cm and 4.1 cm, respectively. The velocity profiles measured by BD show a maximum velocity core below the free surface near the left bank where the water is deepest. This detail is possible because the BD is capable of resolving the velocity distribution in the near surface layer, which enables the detection of the maximum velocity core below the free surface. The composite velocity distribution further confirms the existence of a maximum velocity core.

Recent advances in measurement techniques have suggested the use of remotely measured surface velocity to determine river discharge. The validity of this approach hinges upon, in part, a stable relationship between the water column mean velocity and the surface velocity. Using the detailed velocity profiles measured in this study, the computed mean velocity to surface velocity ratio is in the range of 0.80 and 0.93 with a mean value of 0.88; while the theoretical value is 0.85. Since the velocity ratio falls in a small range, using a mean value to compute the river discharge would probably not be a major source of error. Since this conclusion is only based on a small sample of measurements from this study and from measurements at a few other sites not discussed in this paper; it is recommended that detailed velocity distribution be measured in rivers with a wide range of width to depth ratio, a variety of bed roughness and bed material, and for high flow and low flow regimes. Only after examining a sufficiently large number of case studies can a conclusive assessment of the appropriate choice of the mean to surface velocity ratio be possible for the computation of river discharge.

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